Horizontal Wind Estimates
Deterministically Derived from
the STS-1 Entry Flight Data--
a Comparison with Available
Meteorology Data

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ABSTRACT

Two wind profiles have been determined from STS-1 entry flight data based on AMA, Inc.'s preliminary Best Estimate Trajectory (BET). The deterministic process used in deriving the atmospheric winds requires inertial estimates of the spacecraft angle-of-attack (α) and side-slip angle (β) from the BET in conjunction with some air data system measurements of the actual angles. The current Orbiter Air Data System (OADS) provides the necessary α information. Two β profiles were adopted. The first profile simply assumed that the spacecraft would weathervane into any prevailing wind, i.e., $\beta(t) \equiv 0$. The second assumed a conservative side-slip history computed from measured accelerations in the spacecraft body axes. It is shown that there are no major differences between the deterministic winds computed using both methods. Further, comparisons of these winds with "raw" measurements from Tehachapi, California, and preliminary winds obtained from the LaRC LAIRS file and the JSC/TRW descent BET are presented. The deterministic winds agree favorably with the Tehachapi measurements which are considered the best available reference data because of close proximity to the flight path. Inconsistencies in the wind profiles obtained from the three sources of "measurement" data are noted.

Background

Post-flight BET generation can provide for an excellent inertial spacecraft state and attitude estimate throughout the entry flight. Aerodynamic performance evaluation requires the BET together with some measure of the atmosphere (including winds) encountered. The LaRC Aerodynamic Coefficient Measurement Experiment (ACME) utilizes combined meteorology measurements and models to define the required atmosphere. This atmosphere is translated in time and space to the Shuttle ground track and vertical profile as dictated by the BET history. Dissemination of these data is accomplished via a LAIRS[(1)] file. AMA, Inc. (Ref. 1) utilizes these data to generate an extended BET file to provide ACME investigators with estimates of the atmospheric relative quantities as well as preliminary aerodynamic coefficient estimates. Since most of the extended BET parameters computed are functions of the prescribed atmospheric data, any inaccuracies in the atmosphere directly influence the accuracy of the ACME results. For the most part, few options exist to alleviate this dependence, particularly where pressure, temperature and density are required. However, in situ wind estimation, where possible, could perhaps improve the overall experiment accuracy. At the least, such estimates could be utilized to evaluate the available meteorology data. Thus, it is the purpose of this report to present an in situ wind estimation concept, present results, and to show comparisons with the available meteorology data. Such comparisons can provide considerable insight as to the accuracy of the meterology measurements as well as the adequacy of such data. One must keep in mind that in some instances atmospheric wind measurements may be made at different times and locations than the actual entry flight and must be projected to the ground track/vertical profile of the spacecraft. The accuracy with which this mapping can be done is certainly hard to determine. Obviously, meteorological measurements taken in the immediate vicinity of the ground track, and nearly simultaneous in time, would minimize this mapping requirement but may

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[(1)] Langley Atmospheric Information Retrieval System

not always be operationally expedient. (Fortunately, for STS-1, these data were available[2]). Further, even if both time and spatially optimum, any meteorological measurement inaccuracy would directly affect the winds and, if significant, would need be accounted for in some manner.

Post-flight analysis of STS-1 data has shown evidence of real concern for the dependence on varying treatments of the meteorological data per se. Two available wind profiles[3], one from the LaRC LAIRS file and a second deduced from NASA JSC/TRW's final descent BET, yield side-slip angles (large and quite different) during the lower 80,000 ft. altitude range which has concerned investigators. (see Figures A-1 and A-2 attached as Appendix A). Time zero throughout corresponds to an epoch of $17^h 42^m 30^s.0$ on Day 104. Specifically, the region of concern is the time interval from $t \cong 1950$ sec to $t \cong 2100$ sec. This corresponds to an altitude interval between $h \cong 75,000$ feet and $h \cong 38,000$ feet. Mach no. varies throughout this interval from $M \cong 2.0$ to $M \cong 0.8$. Note that the large side-slip angles computed (~ 3.0 deg) beyond this time are not as questionable based on flight data, principally the rudder deflections. Throughout the specified interval, the rudder deflections are inconsistent with large side-slip angles as seen in Figure A-3. The deflections are shown to be within $\pm$ 0.5 degrees which would indicate near zero side-slip excursions, at least zero on the average. Further, use of the "raw" winds measured at Tehachapi, Calif. does yield more reasonable side-slip estimates throughout this interval. (See Fig. A-4). In any event, without further analysis, these profiles represent three plausible (perhaps) winds during the STS-1 entry flight. Though one would expect the Tehachapi data to be more representative, some added insight could be expected given an in situ estimate of the winds.

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(2) Wheeler Ridge, Calif., and Tehachapi, Calif. measurements received via JSC/Marshall Spaceflight Center

(3) The source or treatment of the meteorology data is unknown.

Deterministic Wind Estimation Concepts

The tri-redundant Inertial Measurement Unit (IMU), or the Aerodynamic Coefficient Identification Package (ACIP), each calibrated as required, can, in concert with the external tracking data from the ground based radars, yield a very good estimate of the inertial entry state vector time history and Shuttle attitude as well. Assuming no winds present the computed angle-of-attack and side-slip angle throughout the entry flight represent "inertial" quantities. In truth, along with the bank angle, they represent a set of Euler angles relating the Spacecraft to the planet relative velocity vector. This suggests the need for an air data system to provide air relative measurements of the spacecraft attitude history, α (t) , β (t). Development of the Shuttle Entry Air Data System (SEADS) will ultimately provide this capability over the entire speed regime. For STS-1, estimates of α (t) below Mach 2.5 were available from the OADS. In lieu of measurements, some assumptions re the β time-history can be utilized to complete the required data set to obtain a first order estimate of the horizontal wind profile. Two methods were considered.

The first method assumed that the spacecraft would weathervane into any prevailing wind, i.e., β (t) $\equiv 0.^{\circ}0$. Certainly one could not expect that the side-slip angle would truly be zero everywhere throughout such a dynamic interval as suggested by the measured rates and accelerations presented in Figure 1a and 1b, respectively. One could expect non-zero excursions to occur as transients with zero mean. Non-zero excursions would, and do, show up on a deterministic profile as high frequency wind components. Also, one could not expect true zero steady-state side-slip conditions during roll maneuvers in this region. Pre-flight nominals indicate side-slip angles on the order of a few tenths of a degree over several hundred seconds. Nonetheless, several tenths of a degree predominant side-slip deviation from the assumed zero value, when compared with inertial values of 3 to 4 degrees, does not strongly influence the deterministic wind computation. Of course, any large biases in either the OADS derived α (t) or the assumed β would necessarily bias the deterministic wind estimate. Given the above guidelines, a horizontal deterministic wind profile can be

generated. No a priori wind estimates are required nor are models (or estimates) of the atmospheric temperature, pressure, and density.

The second method, also independent of any presumed atmosphere but likewise dependent on any OADS biases, conservatively computes the side-slip profile from the measured body axis accelerations[4] as follows:

$$\beta_c = -\tan^{-1} \frac{A_y}{\sqrt{A_x^2 + A_z^2}} \tag{1}$$

Based on pre-flight simulations, side-slip angles compared with similarly computed values using pseudo acceleration data generated from a nominal reference trajectory showed a conservatism of approximately a factor of 2 to 4. However, apart from scale, the computed β followed the reference β history very well. Two heuristic arguments would vindicate these simulation results as well as confirm the conservative qualifier used for the actual flight data computations. First, under somewhat steady-state considerations, a small angle of side-slip can develop when the spacecraft is subjected to a cross-wind. A rudder deflection is required. If for example that side-slip angle were positive (nose-left) a right rudder would be required to counteract any disturbance causing the positive crab angle, assuming the lateral damping (C_{n_β}) were insufficient to overcome the disturbing force. In such an instance, the side force (lateral acceleration) would be additive from both the rudder and the inherent side-slip angle. A side-slip angle computed from the y-body acceleration would be larger than actual to accommodate the contribution from the rudder. Similarly, the forces from both the side-slip and rudder would be additive if the disturbance were in the opposite sense. A second argument is more dynamic in nature in that it involves the roll-yaw cross coupling. Pitched up at a positive angle-of-attack a spacecraft develops a positive side-slip angle during the early portion of a positive rolling maneuver. This produces a negative side force and that from the required rudder deflection to null the side-slip to effect a coordinated maneuver is also negative. Further, any side force due to the

[4] derived data from IMU2

positive rolling rate would develop in a negative y direction. Again, to account for the entire side-force developed using a single parameter (i.e. side-slip angle) is conservative. Obviously, to trim the spacecraft at a non-zero side-slip angle in the absence of any disturbance (winds) would require the opposite rudder and these side forces would not be additive. In any event, determination of side-slip from accelerometry is not readily characterized with static or simplified dynamic models. Use of the spacecraft control surface telemetry (to define the configuration), pre-flight aerodynamic derivatives, and measured rates and accelerations in a more rigorous algorithm may be plausible.

Figure 2 shows the computed β utilized in the second method. The angle-of-attack from the OADS measurements are also shown thereon. This α "measurement" is, of course, common to both methods. Thus, Figure 2 shows the measured (and assumed/computed) air data system parameters utilized for the two deterministic wind profile computations, keeping in mind that the first method assumed null values for β throughout. Given that the second method computes conservative estimates of the side-slip history, and further, since the first method optimistically evokes an exact zero β profile, the deterministic wind profile computed using the two data sets should represent a reasonable expected range on the atmospheric winds.

Discussion of Results

The preliminary BET obtained by AMA, Inc. (AMABET2)[5] was utilized to describe the inertial state and attitude time history for the STS-1 entry flight. Given an estimate of the "true" α (t) from the OADS[6] and, for want of better information, the previously discussed assumptions of side-slip, it is possible to deduce deterministically a horizontal wind at sime time to force the inertial and "actual" angles to agree. Such instantaneously mapped winds, deduced from Mach $\cong$ 2.0 to near touchdown, were computed and are presented versus altitude to yield the two in situ profiles. In terms of altitude, the region for which the wind profile was estimated is below ~ 80,000 ft. Figure 3 shows the altitude versus time over the interval.

The feasibility of the deterministic winds can perhaps be judged by comparison with preliminary winds obtained from LaRC and JSC. These latter winds were obtained from (1) a preliminary LAIRS file (USE 2, vintage June 29, 1981) which are thought to be based on measurements at Barking Sands, Pt. Magoo, and Edwards, (2) the final JSC/TRW descent BET[7], and (3) Marshall Spaceflight Center measurements at Tehachapi, Calif. (received via JSC).[8]

Shown in the accompanying figures are the comparative data for the two deterministic profiles and the available meteorological data. Wind magnitude is presented in Figure 4 and wind direction is presented in Figure 5. Component winds are presented as Figures 6 and 7 for the North-South and East-West components, respectively. Comparisons of the measurement data sets among themselves show that LAIRS is the outlier in wind magnitude whereas JSC/TRW is the outlier in direction. These discrepancies are probably due to the "preliminary"

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[5] The preliminary BET is sufficiently accurate throughout this interval which indicates the particular BET chosen is relatively unimportant in determining the wind profile.

[6] Actually, the G and C alpha (measurement V94H3021C) was used and assumed to be derived from the OADS below Mach 2.5.

[7] Meteorology data on the JSC/TRW final BET may perhaps be considered preliminary also though here it simply serves for another basis for comparison.

[8] These data, as well as measurements from Wheeler Ridge, Calif., were taken near and essentially concurrent with the STS-1 landing.

qualifier assigned to these winds and should be helpful in refinements of the preliminary data. Both sets of deterministic winds agree favorably with one another and with the Tehachapi measurements, although the deterministic winds derived from the non-zero β show much more scatter.

Component comparisons show that the LAIRS Westward component is generally biased from the deterministic data ($\sim$ 20-30 ft/sec) throughout much of the interval but the Southward component agrees quite well. The opposite is true for the JSC data. It almost appears that the Southward JSC component was reflected though care has been exercised to make all comparisons with consistent sign conventions.

Referring once again to the side-slip phenomenon as discussed in the Background Section of this report, it is apparent that the deterministic wind required to null (or minimize, conservatively speaking) the side-slip angle throughout this region is perfectly reasonable, compares quite well with what would appear to be the best meteorological data available (Tehachapi) and exhibits some of the characteristics of the other available meteorology data. It is perhaps questionable to accept these deterministic winds as absolutes yet comparable solutions were obtained for two quite different side-slip assumptions.

Conclusions and Recommendations

The deterministically derived horizontal wind profiles based on STS-1 flight data appear to be feasible. The accuracy of these winds is not limited by the particular choice of BET, but rather by any biased α estimates from the OADS and the required side-slip assumptions used. Thus, the winds cannot be taken as absolutes but are certainly worthy of consideration.

Basically the disadvantage of any in situ wind estimator is the dependence on an air data system. For future flights SEADS will be available. In the interim, some side-slip estimation capability from the OADS measurements would be desirable if possible. Pseudo air data parameters (at least α and β) could be generated based on the control surface telemetry, a reasonable BET and some pre-flight aerodynamic data base. Here some dependence on an atmospheric model (at least density and temperature) is required. Though more complex, the concept is similar to that used during the Viking aeroshell phase (Ref. 2) wherein a nominal trim angle-of-attack versus Mach No. ($\beta \cong 0$) was employed. In any event, this process would be iterative.

Beyond the deterministic wind algorithm (given or assuming some air data system to be available) some improvement could be obtained by filtering to obtain more statistically significant wind estimates since the deterministic estimates will exhibit higher frequency components, e.g., if β is oscillatory. Of course, biases degrade any process significantly. An advantage of any in situ estimate is that during the lowermost altitudes when the spacecraft has slowed down appreciably large erroneous estimates are unlikely if the air data parameters (or those assumed) are accurate to only a few tenths of a degree. On the other hand, extrapolated meteorology measurements could induce considerable α, β excursions from the truth dependent upon the proximity (time and space) of the measurements themselves.

References

1. Findlay, J.T., Kelly, G. M., and Henry, M. W., "An Extended BET Format for LaRC Shuttle Experimenters: Definition and Development", AMA Report No. 81-11, June 1981.

2. Findlay, J., "Atmospheric Density Reconstruction Accuracies Using a Wind Estimator During the Viking Aeroshell Entry", AMA Report No. 72-51, November 1972.

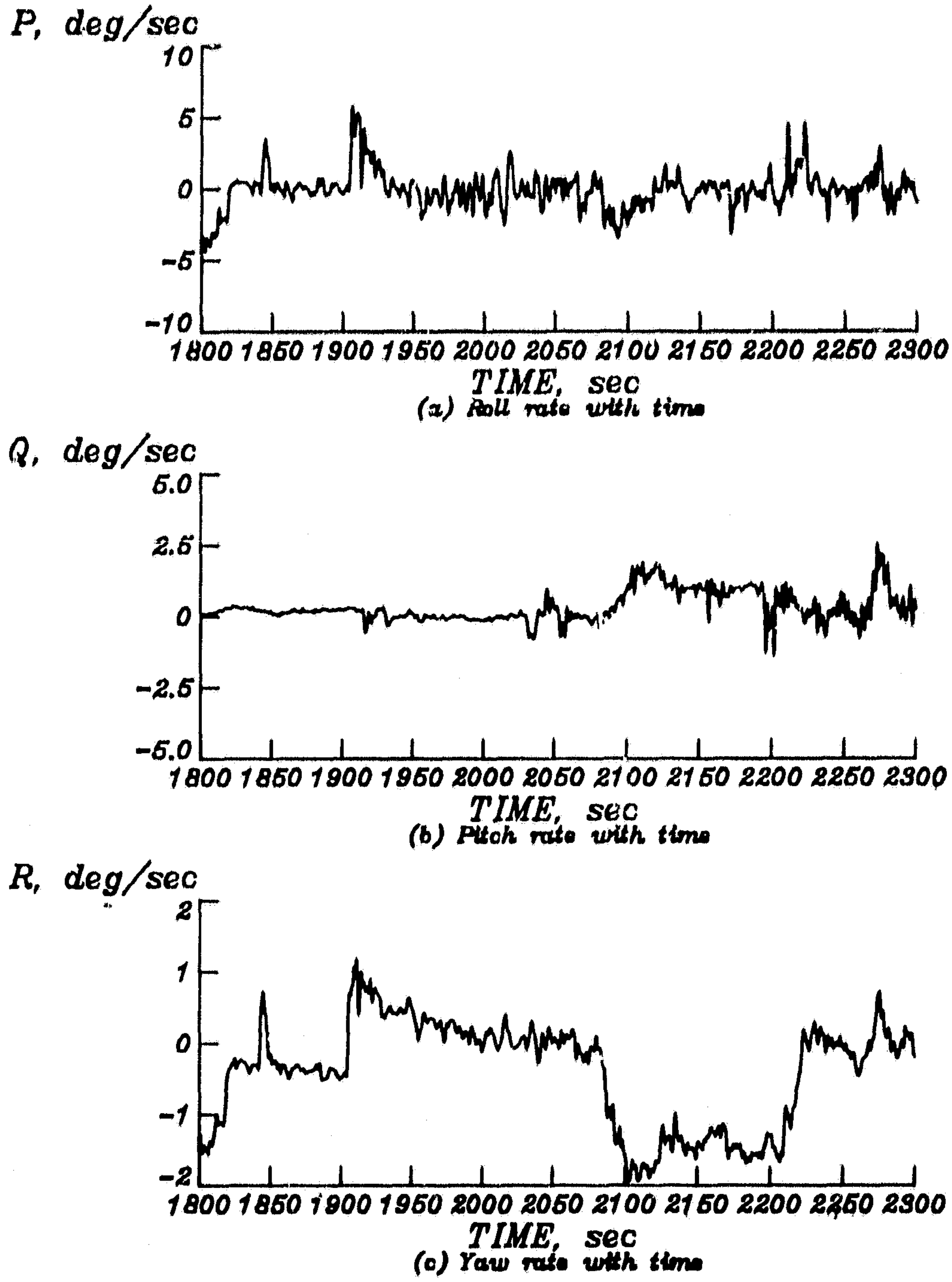

Figure 1a. STS-1 body axis rate history during lower altitude interval (from ~ 110,000 feet)

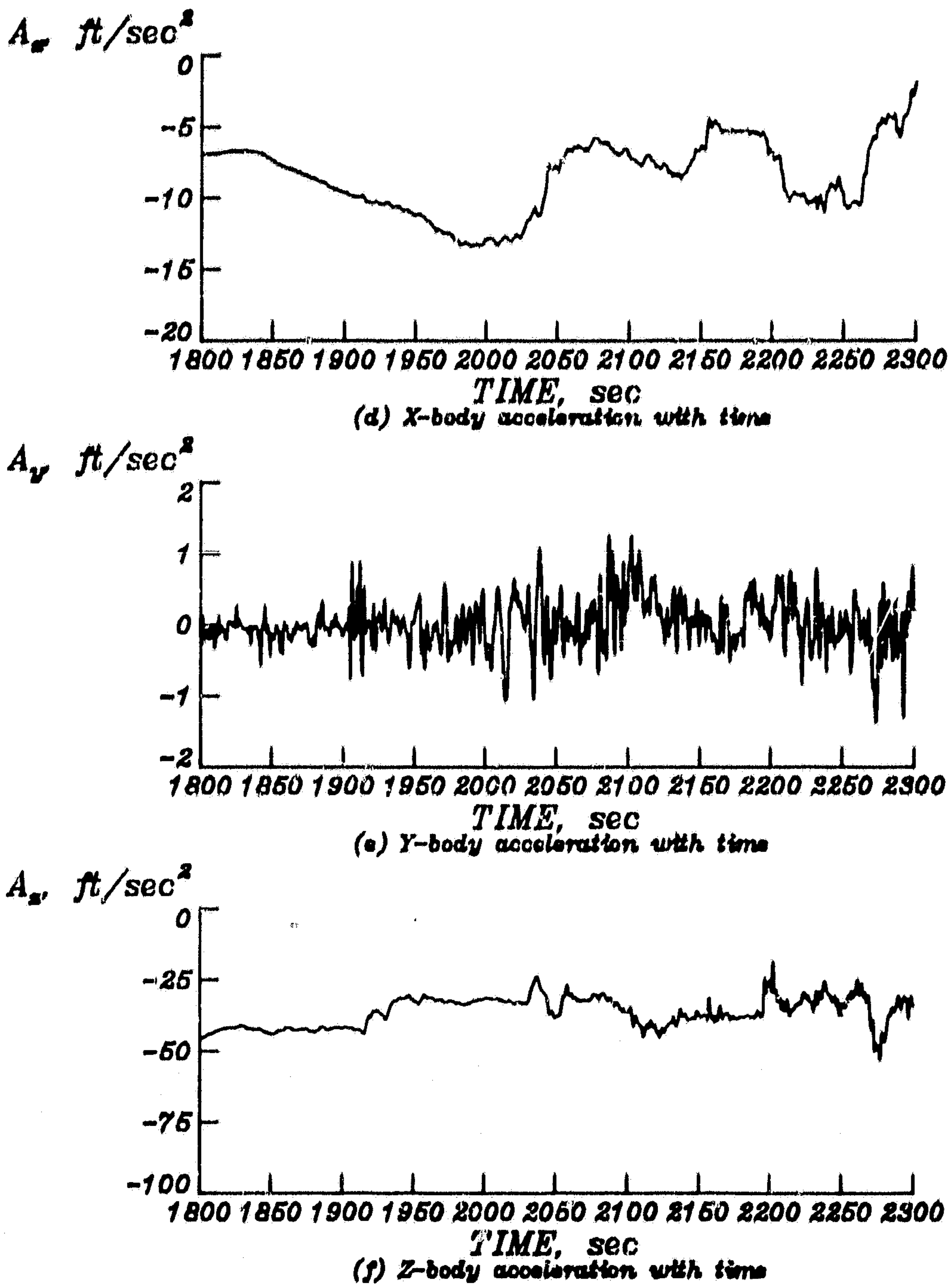

Figure 1b. STS-1 body axis acceleration history during lower altitude interval (from ~ 110,000 feet)

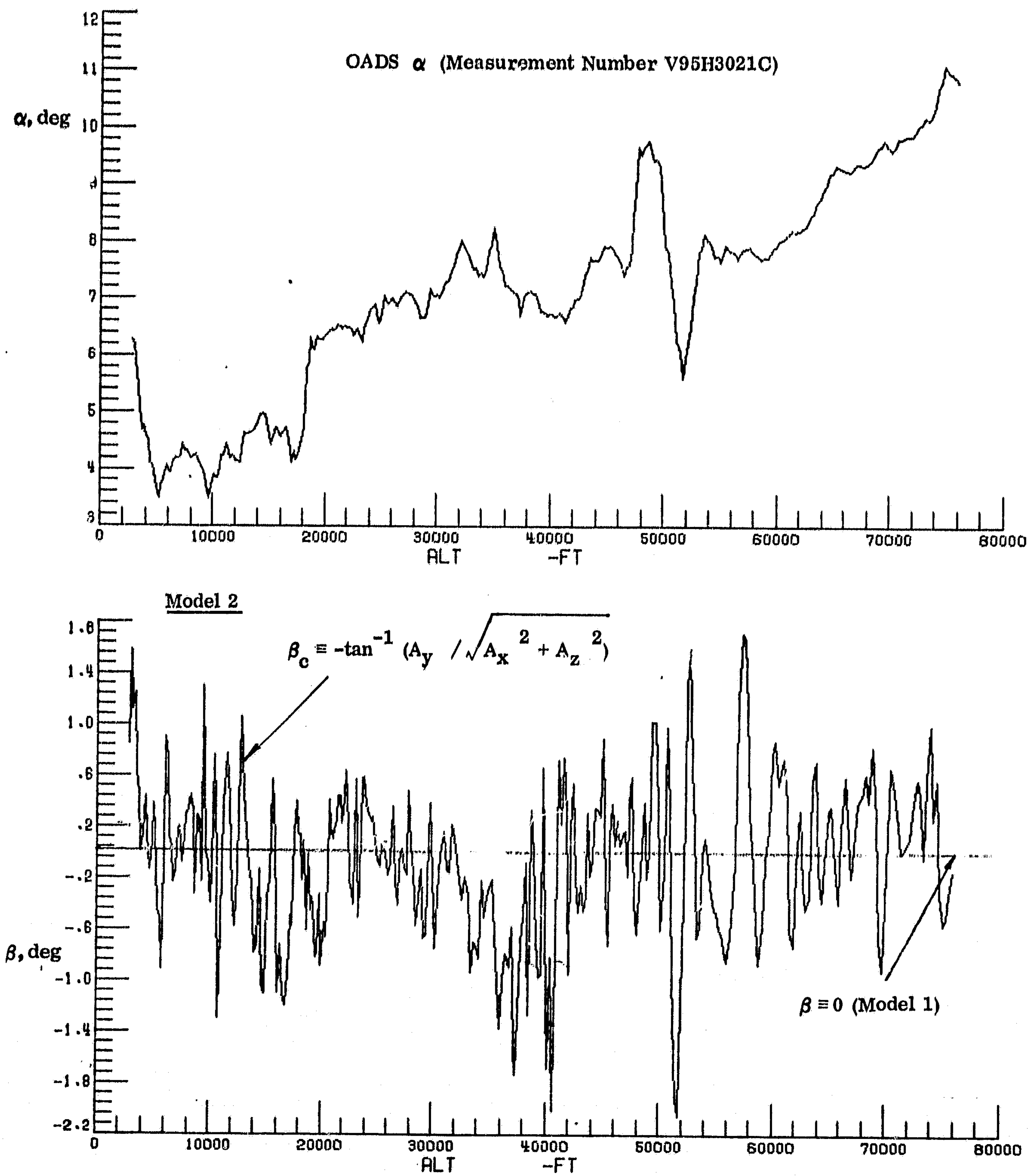

Figure 2. Air data parameters for deterministic wind estimates

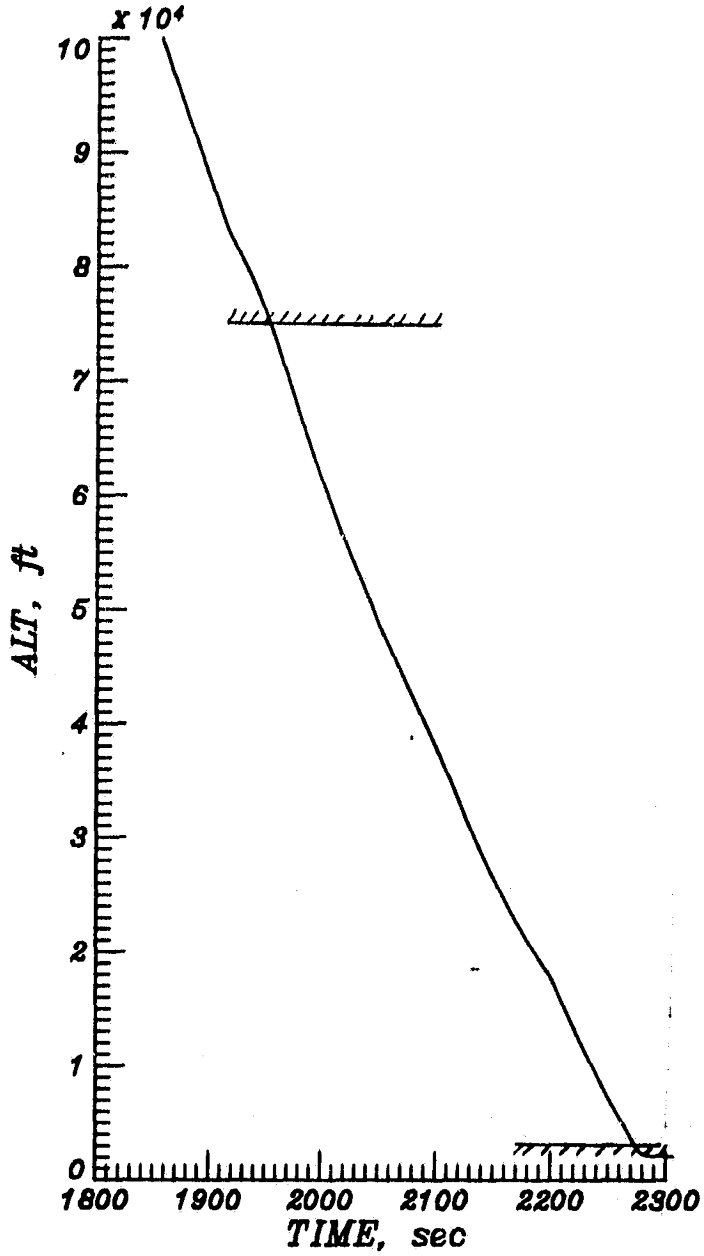

Figure 3. Altitude history from AMABET2 used for deterministic wind estimate

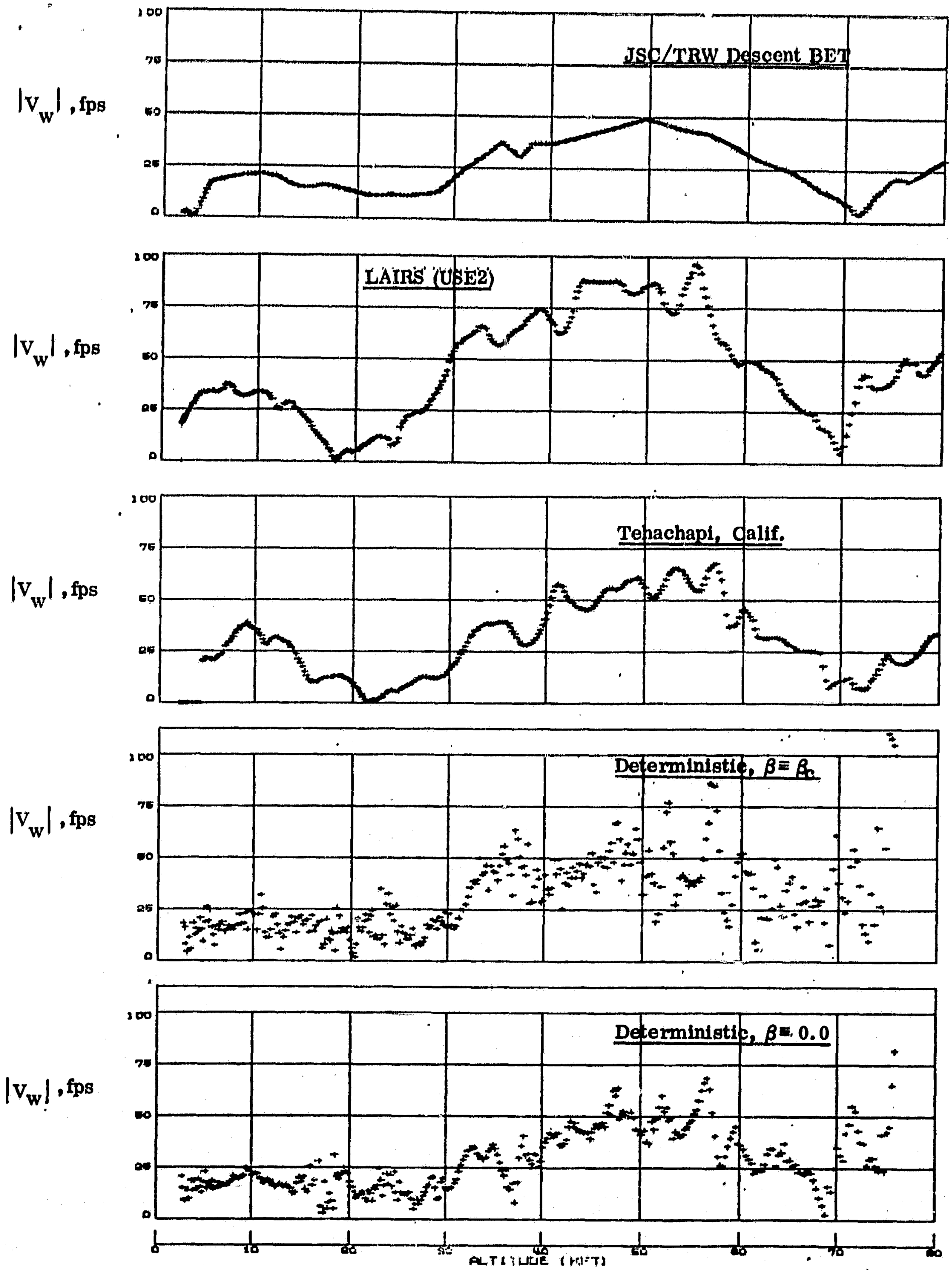

Figure 4. Wind magnitude comparisons for STS-1

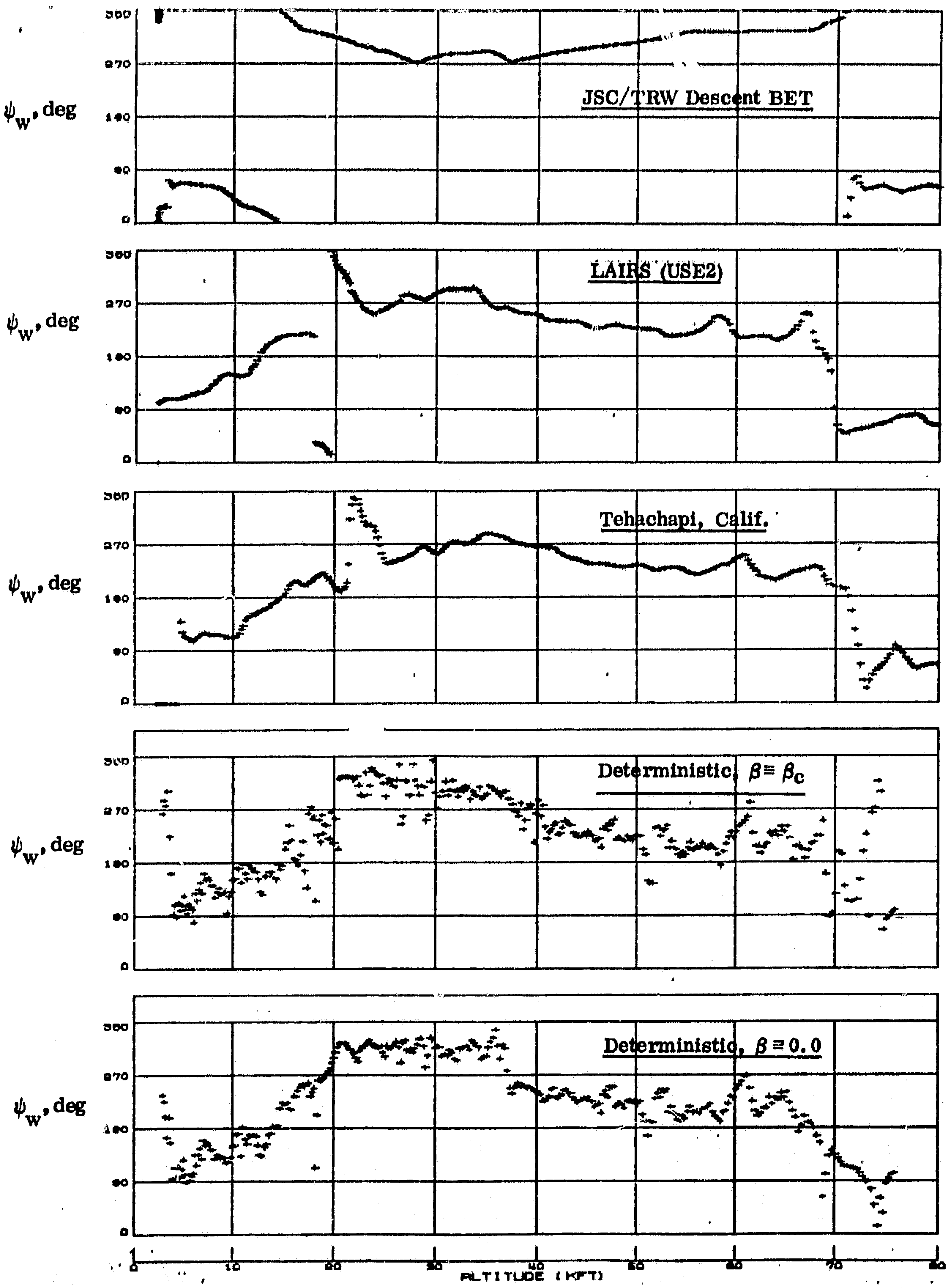

Figure 5. Wind direction comparisons for STS-1

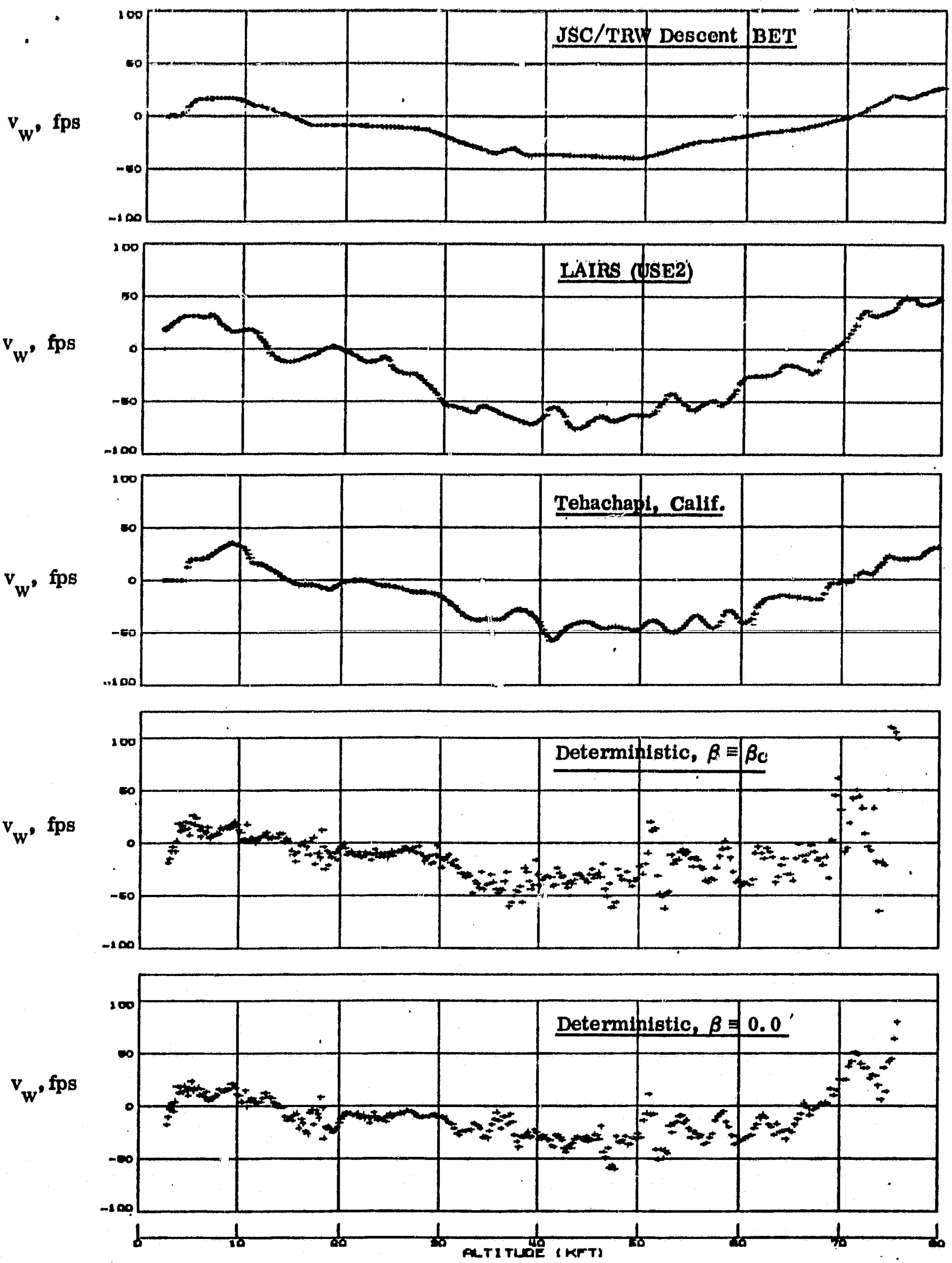

Figure 6. Westward wind component comparisons for STS-1

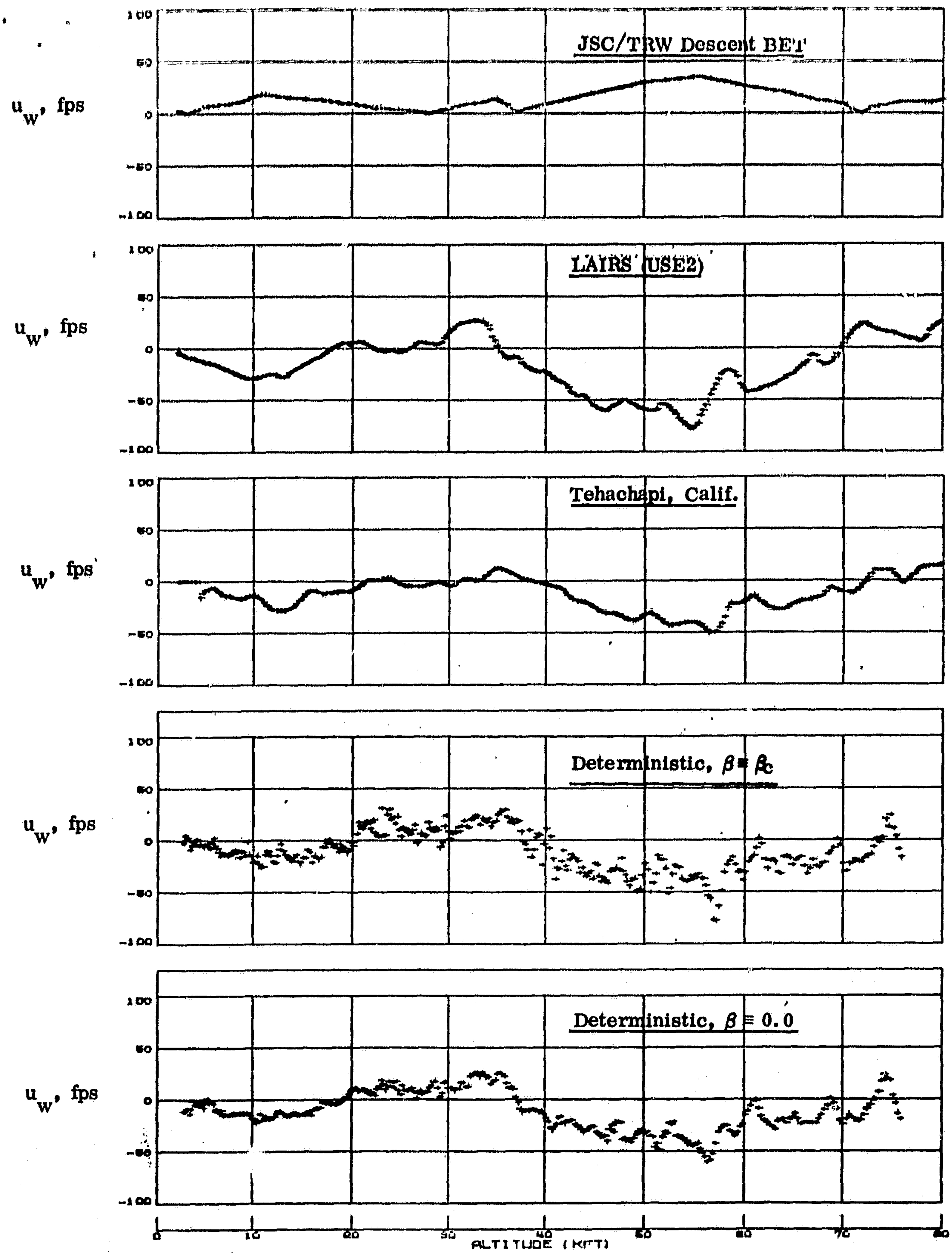

Figure 7. Southward wind component comparisons for STS-1

APPENDIX A

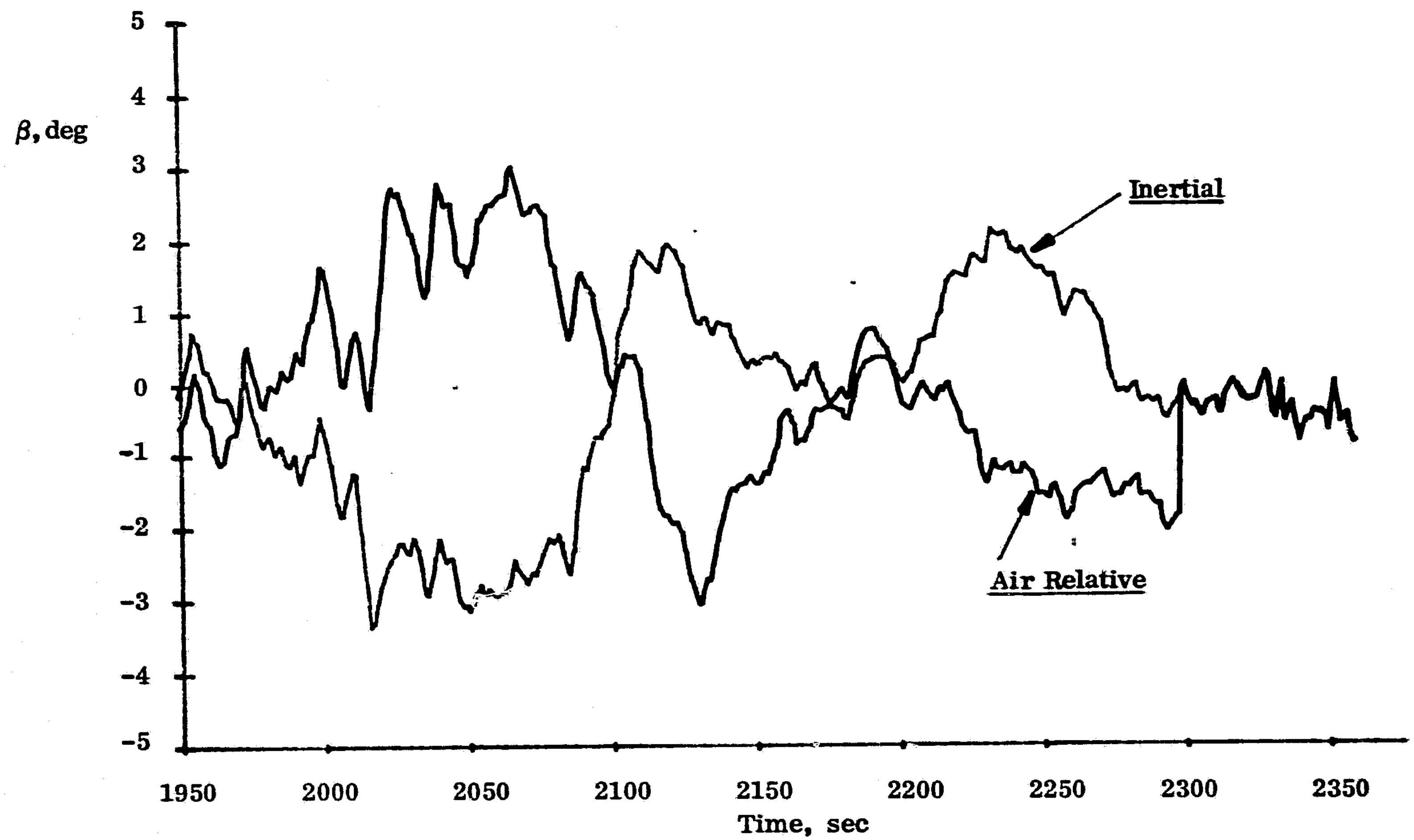

Fig. A-1 Inertial and air relative side-slip angles from AMABET2/LAIRS(USE2) descent BET

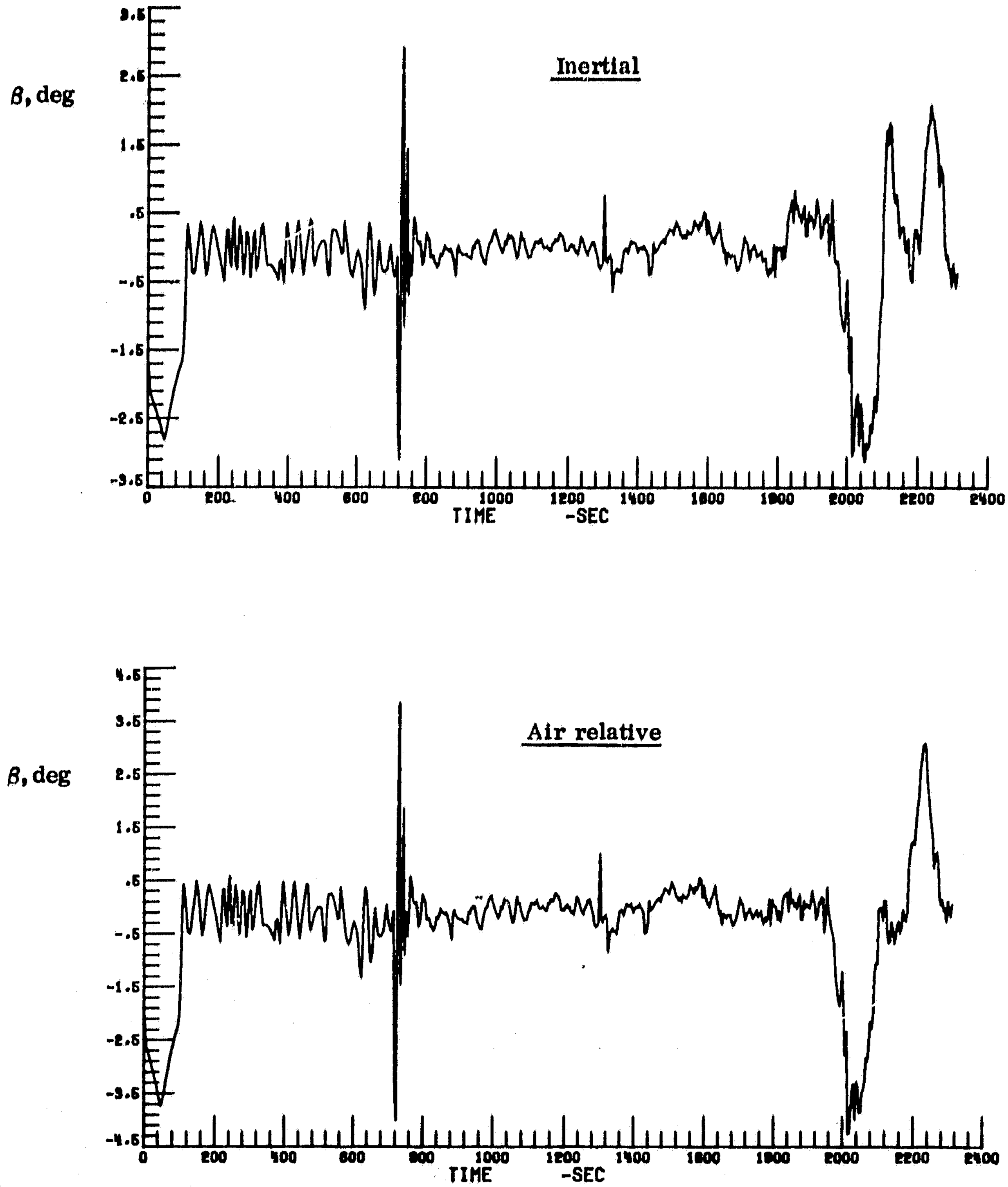

Figure A-2 Inertial and air relative side-slip angles from JSC/TRW final descent BET

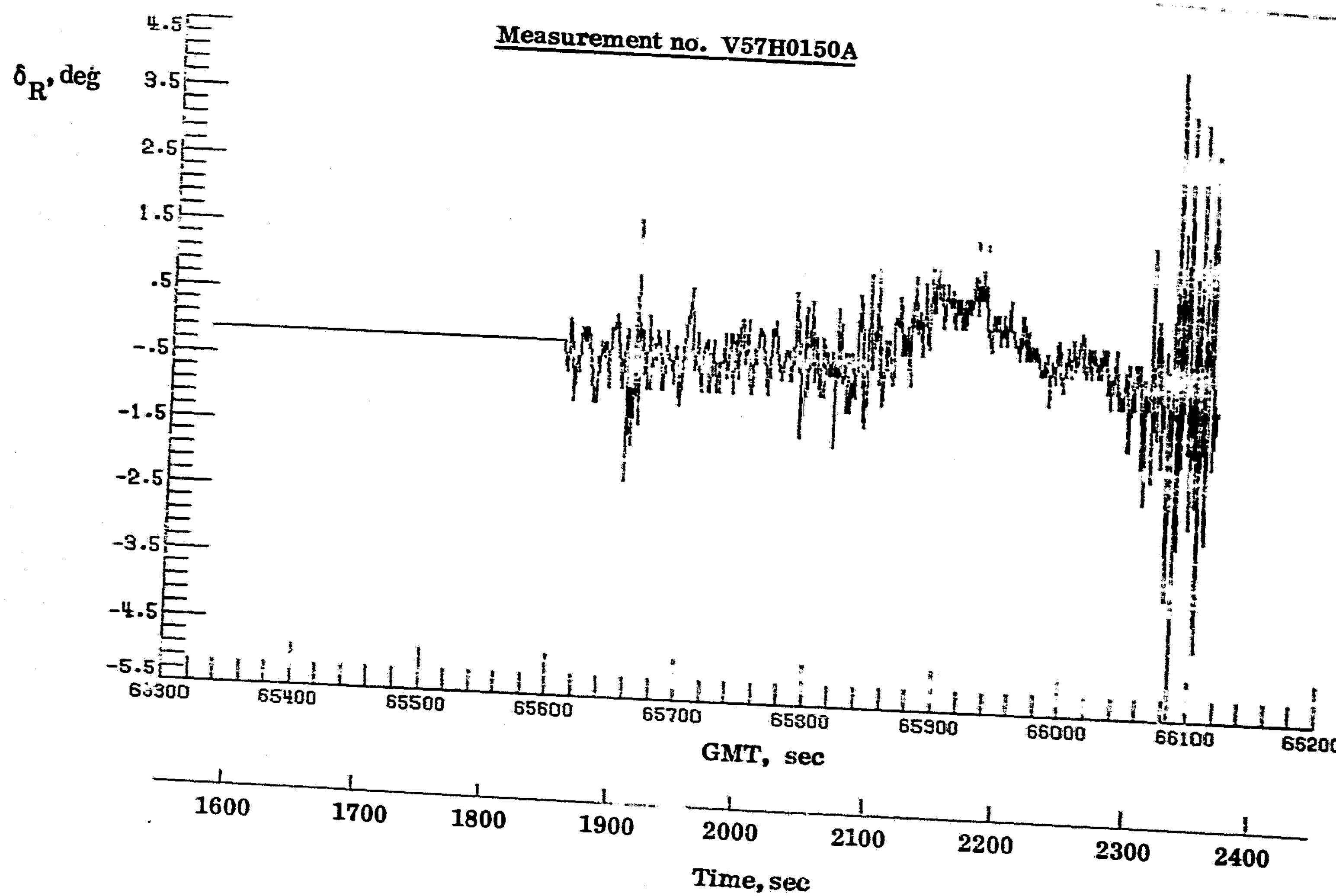

Figure A-3 STS-1 Rudder deflection history during lower altitude region

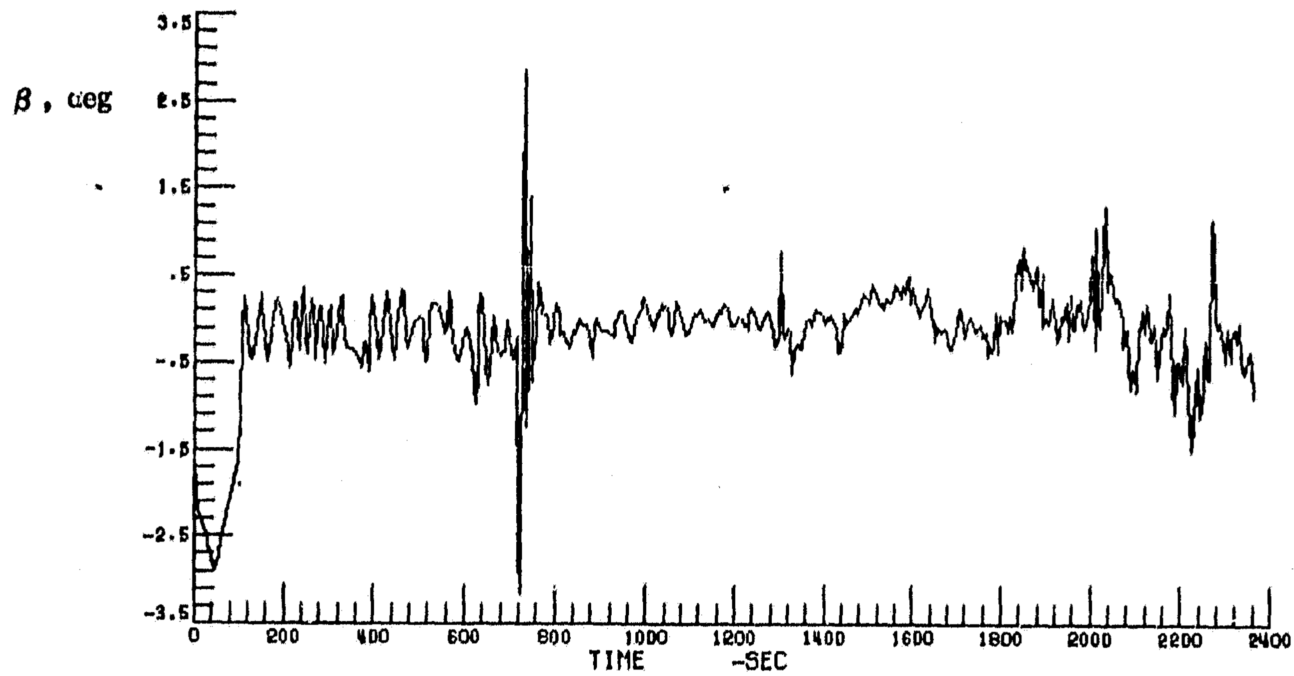

Figure A-4 Air relative side-slip angle using AMABET2 and Tehachapi, Calif. meteorology measurements taken at 18^h18^m GMT on 14 April, 1981.